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# Meta-analysis of high penetration renewable energy scenarios

Jaquelin Cochran [a,*], Trieu Mai [a], Morgan Bazilian [b]

[a] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA
[b] Joint Institute for Strategic Energy Analysis, NREL, Colorado, 15013 Denver West Parkway, Golden, CO 80401, USA

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ABSTRACT

We provide a meta-analysis of several recent analytical studies that evaluate the possibility, operability, and implications of high levels of renewable sources of electricity (RES-E) in power systems. These studies span different geographic regions, rely on a range of analytical methods and data assumptions, and were conducted with differing objectives. Despite the differences, these studies share some common conclusions, one of which is that renewable energy resources can play a large role in future power systems. Moreover, most of the studies address aspects of integrating these resources into system operations, and all of them conclude that RES-E can supply, on an hourly basis, a majority of a country's or region's electricity demand. We compare the analytic approaches, data inputs, and results in an effort to provide additional transparency and information to policy makers.



**Contents**



## 1. Introduction

Decision-making in the energy sector is frequently informed by the results of analytical models. Yet these models differ significantly in their theoretical frameworks, assumptions, and scope, among other parameters [1]. An understanding of how these factors affect results is necessary to allow comparisons across energy analyses and elucidate key insights to inform policy.

A wide literature (i.e., [2–9]) and several major forums (the Energy Modelling Forum, the Innovation Modeling Comparison Project, the United States Climate Change Science Program, the CAse Study Comparisons And Development of Energy Models for INtegrated Technology Systems (CASCADE-MINTS) project, and the Intergovernmental Panel on Climate Change Working Group III) explore and compare energy, climate, and integrated assessment models (IAM).[1] IPCC [6] reports that over 750 emissions scenarios exist in the literature – all of them have treatment of the energy sector at some level. Comparisons of these many models and approaches are difficult, but these efforts suggest that comparisons with “smaller” system boundaries (such as just around the electricity sector) are useful in better understanding how such analytics can inform decision-making.

* Corresponding author. Tel.: +1 303 275 3766.
*E-mail address:* jaquelin.cochran@nrel.gov (J. Cochran).

[1] Tol [10] reviews IAMs, which are broader in scope than the energy sector models and are difficult to compare within the scope of this paper.

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This paper reviews a small sub-set of the energy modeling literature, namely recent research focused on scenarios that describe a future with high penetrations of renewable energy (RE) in power systems.[2] The purpose of this meta-analysis is to compare the analytic approaches, data inputs, results, and policy implications in the specified literature, and thereby provide additional transparency and information to policy makers.

Section 2 explains the methodology of the meta-analysis. Section 3 reviews literature specific to recent high penetration studies for the generation of electricity from RE sources. Section 4 presents a comparative analysis of high RES-E studies. Section 5 assesses implications for policy makers; it is followed by a conclusion.

## 2. Methodology

To conduct this meta-analysis, we focus on the following national and global high RE scenarios, organized by the geographic scope of the study:[3]

- *Australia*: [11].
- *Denmark*: [12].
- *European Union*: [13].
- *Germany*: [14].
- *Global*: [15].
- *Global*: [16].
- *Global*: [17].
- *Ireland*: [18].
- *New Zealand*: [19].
- *Portugal*: [20].
- *United Kingdom*: [21].
- *United States*: [22].

We compare qualitative and quantitative attributes of each study. Qualitative attributes include the study's scope and objectives, the models and modeling framework—including assumptions and sensitivity analyses—and implications for RES-E support policies and power system operations. Quantitative attributes that the paper analyzes include projections of demand, capital technology costs, discount rates, carbon prices, electricity prices, and electricity generation mix.

The studies vary significantly with regards to assumptions and complexity of analysis. The meta-analysis contributes to scholarship by assessing how these differences affect implications for decision-makers, and if there are policy conclusions that transcend these differences. The meta-analysis also reveals gaps in analysis for high RES-E studies—areas where further research and analysis will be critical to advancing our understanding of pathways to and impacts of high RES-E futures.

## 3. Literature review of high penetration of RES-E studies

Comparisons of energy scenarios are frequently made in the literature to assess the range of energy futures and address plausibility (see, e.g., [25,26]). An example of such a comparison is illustrated in Fig. 1, which plots the results from a number of energy scenarios in respect to the penetration of RE technologies, ranging from 10% to 80% in 2050 [26].

Recently, high penetration scenario studies that model the potential to reach 50–100% penetration rates by mid-century for national, regional, and global RES-E penetration have been published. The motivations for these studies vary and include goals of climate change mitigation [17], optimized resource use [18], and better understanding of technical challenges of large-scale renewable deployment [22]. The substantial growth in RES-E penetration over the last decade [27] has spurred increased attention to evaluate high RE scenarios globally.

Scenarios for very high penetration of RES-E (e.g., 100%) often stir controversy [28,29] in part because they do not always include a sufficient consideration of the system complexity required to instantaneously match supply with demand at high RES-E penetrations. This balance under high RES-E futures may require modifications to wholesale power markets, system operations, and transmission grids, among others [30–35], which can be challenging to model. Still, the value of scenarios is often in their illumination of key questions or obstacles to further expansion and research of RE in electricity markets.

## 4. Comparative analysis of high RES-E studies

The motivations, modeling frameworks, input assumptions, and study scopes all play significant roles in determining scenario design and results. Although some of the studies modeled the full energy economy, in this paper we narrowly focus on the power sector and all of the percentages cited are for the power sector only. Regardless of actual penetration selected, the high RES-E fractions modeled across these scenarios represent a significant departure from today's low RE systems.

Table 1 summarizes for each high penetration RES-E study the geographic and economic scopes, scenario year, scenario motivation, model used, model framework, and penetration level. Following a description of these aspects, this section compares demand and cost input data, as well as key results, including technology mix in generation, projected costs, and sensitivity analyses.

### *4.1. Scenario design and tools*

All the studies are designed at least in part to assess the feasibility of dramatically scaling up RES-E, primarily to reduce carbon emissions; nevertheless, the scenarios vary in their approach. For example, some model just the power sector (e.g., [13,14]), whereas others (the global scenarios [12,18,21]) offer an economy-wide, integrated assessment of low carbon futures. Three studies [11,19,20] are designed to evaluate the feasibility of RES-E scenarios from a perspective of resource adequacy, independent of cost considerations. These studies are not projections; instead they analyze the possibility of 100% RES-E to meet demand for a given year using historic data (demand, meteorology), different combinations of RES-E supply (scaled up from historic levels), and prescribed dispatch order. Connolly et al. [18] structured their study similarly, but used cost assumptions in the dispatch optimization model. Other studies also include costs—some in dispatch optimization for the scenario year (e.g., [12]); others as part of capacity expansion modeling and to estimate potential incremental costs relative to the reference scenarios of achieving high RES-E outcomes (e.g., [22]). Transmission constraints characterize other differences, as demonstrated in Elliston et al. [11], which assumed no transmission constraints; whereas other studies [13,14,22] model highly spatially resolved scenarios that include grid constraints. The scenarios also vary in terms of interconnections—for example, ECF [13], SRU [14], and Krajacic et al. [20] evaluate multiple scenarios that vary the extent of imports and the use of larger areas to allow balancing.

[2] High penetration is defined as RE that generates at least 80% of the total electricity supply.

[3] We also reviewed a 100% renewable energy scenario for Macedonia [23], however did not include it in our comparative analysis as it used the same analytic tool as in [12,18]. We did not review subnational studies, such as Nelson et al. [24]; some subnational studies have larger generation capacities than national studies, and contribute to the dialogue on high RES-E futures.

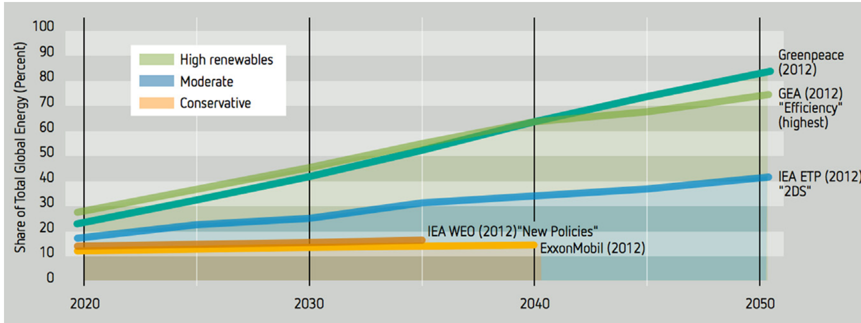


**Fig. 1.** Conservative, moderate, and high-renewables scenarios to 2050 [26].

**Table 1**
Design comparison of RES-E scenarios.

| Geographic scope | Study | Economic scope | Scenario year | Scenario motivation | Models used | Model framework | Penetration level (%)[a] |
|---|---|---|---|---|---|---|---|
| Australia | Elliston et al. [11] | Power sector | 2010 | Identify and quantify challenges to reliably supply 100% RES-E | Python-written program | Simulation of hourly generation using historic data (meteorology and electric industry data) and prescribed dispatch order for hypothetical power generators | 100 |
| Denmark | Lund and Mathiesen [12] | Economy-wide | 2050 | Evaluate technical and economic capability to achieve 100% RE system, using targets for carbon reduction, energy security, and employment and export | EnergyPLAN | Forward and back process to develop individual proposals, which were integrated in economy-wide hourly dispatch model | 100 |
| European Union | ECF [13] | Power sector | 2050 | Investigate technical and economic feasibility of achieving 80% reduction in $CO_2$ below 1990 by 2050, maintaining energy security; highlight critical path decisions and requirements for next 5–10 years | Various[b] | Hourly dispatch that optimizes requirements for transmission, backup plants, and balancing; demand reflects all sectors achieving 80% $CO_2$ reductions | 80 |
| Germany | SRU [14] | Power sector | 2050 | Assess technical, economic, and political feasibility of 100% RES-E | REMix | Hourly, least-cost optimization of energy portfolio using high resolution grid | 100 |
| Global | Greenpeace [16] | Economy-wide | 2050 | Describe alternative development pathway and indicate actions to both achieve $CO_2$ reduction targets and phase out nuclear energy | MESAP/PlaNet simulation model | Unknown | 95 |
| Global | IEA 2DS scenario [15] | Economy-wide | 2050 | Explore technology options to ensure 80% chance to limit global temperature rise to 2 degrees Celsius (2DS scenario) | ETP-TIMES | Least-cost optimization to meet final energy demand of ETP scenarios | 57[c] |
| Global | WWF [17] | Economy-wide | 2050 | Assess technical feasibility to achieve 95% renewable energy system, economy-wide | Ecofys designed model | Unknown | 100 |
| Ireland | Connolly et al. [18] | Economy-wide | 2007 | Evaluate technical implications of 100% RES using various fuel combinations, with a goal to reduce $C0_2$ and improve energy security | EnergyPLAN | Deterministic input/output model; hourly simulation, optimizing both technical and economic operations using historic data | 100 |
| New Zealand | Mason et al. [19] | Power sector | 2005–2007 | Explore technical potential for 100% RES-E that maintains lake levels for hydro and reduces energy spillage | Matlab with Excel | Simulation of half-hourly generation by replacing fossil fuels with various combinations of wind, geothermal, hydro, and operational changes | 100 |
| Portugal | Krajacic et al. [20] | Power sector | 2020[d] | Explore technical solutions to achieve 100% RES-E and thereby energy security, and determine how $H_2$RES can be used to calculate larger power systems | $H_2$RES | Hourly simulation that integrates RE and storage in both interconnected and island scenarios using historic data | 100 |
| United Kingdom | Kemp and Wexler [21] | Economy-wide | 2030 | Present one of many modeled options for meeting energy requirements while reducing GHG emissions; provide policy implications | (Future Energy Assessment) FESA energy model | UK Energy Research Centre's scenarios, but using demand data derived from Zero Carbon Britain 2030 scenarios and scaling up RES-E to 99% | 99 |
| United States | NREL [22] | Power sector | 2050 | Provide analysis of grid integration opportunities, challenges, and implications of high levels of RES-E; no market or policy assessment | ReEDS and GridView | Highly spatially resolved models of capacity expansion and hourly chronological production cost modeling | 80 |

[a] Penetration level refers to the share of RES-E in the final electricity generation.
[b] ECF [13] uses a combination of models, none of which have names cited. These include a macroeconomic model from Oxford Economics, a power sector capacity expansion model from Imperial College of London, and an optimization dispatch with a stochastic component.
[c] The RE penetration levels ranged from 80% to 100% across most of studies reviewed (see Table 1); the IEA 2012 [15] scenario, with RES-E penetrations of 57%, was included as representative of "moderate" scenarios [26], and for its "technology rich" description of the energy sector.
[d] The year 2020 was provided as a hypothetical year for achieving 100% RES-E, but the analysis was conducted using historic data.

The analytical tools used to conduct the scenario analyses vary in technical sophistication and detail across the studies, from Matlab with Excel spreadsheets [19] to heavily researched and financed models like EnergyPLAN [12,18].[4] Many of the studies employ least-cost optimization techniques, represented by the models EnergyPLAN, ReEDS, REMix, and ETP-TIMES. NREL [22] employs two models—ReEDS and GridView. ReEDS allows region-specific, long term capacity expansion modeling. The 2050 scenario output for ReEDS served as the modeling basis for GridView, which models system operations at an hourly timescale to more accurately represent, e.g., transmission power flows and required ramp rates of generation plants. The choice of analytic tool appears to reflect the intended audience and study purpose. For example, the use of commercial software in the NREL [22] study reflects the intended utility audience, among others.

One common theme across many of the high RES-E studies is the use of detailed, primarily hourly, time-series data. An analysis of grid operations with significant wind and solar requires time-series data to model the ability of a power system to accommodate the additional variability and uncertainty. Geospatial diversity and transmission needs are also important aspects of RES-E systems and are explicitly modeled in a few of the studies (e.g., [13,14,22]). In addition, all of the studies discuss current infrastructure as a leading inhibitor of higher RE penetration. Several of the studies [11,14,20] model their scenarios with the acknowledgment that grid upgrades may be required to achieve 100% RES-E.

### 4.2. Data inputs: demand

Most studies forecast improvements to energy efficiency, although changes in total demand relative to current consumption varies widely based on the extent of electrification of heat and transport sectors. For example, IEA [15] projects the use of energy-efficient technologies to reduce global energy consumption, but overall electricity demand increases with the adoption of electric vehicles. SRU [14] and NREL [22] evaluate sensitivities around electricity demand, including “low-demand” and “high-demand” growth scenarios. Although four studies use historic data for their analyses [11,18–20], they each conclude that demand reduction is likely a cost-effective approach to reducing unmet demand in future years. Table 2 summarizes the demand data employed for each study.

### 4.3. Data inputs: costs (capital costs, discount rates, carbon prices)

Historically, a major barrier to RES-E penetration has been cost, as it is a key determinant to RES-E deployment. While costs—and ultimately the deployment of RES-E technology—are typically a consequence of innovation and scaled production, political intervention (e.g., fiscal incentives and carbon pricing) can play a major role in lowering costs and accelerating deployment.

Costs are a very significant input assumption for models that provide economically based capacity expansion and/or dispatch. Because the scenarios are not descriptive forecasts but instead normative visions or backcasts for high RES-E scenarios, the capital costs and/or carbon prices in studies with capacity expansion models may have been selected to estimate potential incremental costs of achieving 80%+outcomes relative to the reference scenarios. For example, NREL [22] uses multiple technology cost projections within the least-cost optimization model, which generates a range of incremental electricity price impacts and a range of technology deployment.

[4] We were unable to evaluate the analytic tools used to generate the Greenpeace 2012 Energy [R]evolution scenarios [16] or the WWF The Energy Report scenarios [17], and therefore unable to asses how the modeling framework affects results.

For the scenarios that bypass economically based capacity expansion assessments, costs in some cases were used, post-model, also to estimate investment and electricity costs associated with the model outcomes. However, the deployment results do not vary with cost assumptions in this case. Results from technology cost ranges can help inform public and private decisions on R&D support for different technologies depending on the level of willingness for increased costs (and, potentially, increased benefits).

Not all studies include cost projections. Elliston et al. [11], Mason et al. [19], and Krajacic et al. [20], all of which simulate RES-E scenarios using historic data, prescribe a dispatch order in the modeling, independent of market and economic analyses, and therefore do not assess costs. In other cases, including Greenpeace [16] and WWF [17], it is unclear how cost projections are used. Reedman [36] also concludes in review of a separate set of high RES-E studies that the majority of studies focused on technical feasibility for RES-E to meet demand on a temporal basis and at the exclusion of cost considerations.

Table 3 summarizes example cost inputs, including technology capital costs, discount rate, and carbon price.

### 4.4. Scenario results

The technology mix across the scenarios varies significantly, largely dependent upon assumptions, geographic contexts, and modeling constraints. For example, Kemp and Wexler [21] and SRU [14] envision a majority of offshore wind based on resource availability and projected cost reductions. Mason et al. [19] and Krajacic et al. [20] both employ hydro to integrate variable RE and serve as storage. Lund and Mathiesen [12] and Connolly et al. [18] project significant biomass, in part through CHP, but also because the fuel is projected to power multiple sectors (industry, heating, and transport, including indirectly through hydrogen). ECF [13] models a mix that is not the least cost, instead optimizing diversity to reflect energy security, regional differences, and avoidance of silver-bullet technologies. SRU [14] excludes emerging technologies such as wave and tidal energy due to lack of reliable data. NREL [22] projected technology mixes vary regionally, reflecting the high variation in available resources and transmission infrastructure, however, most scenarios rely on onshore wind to the greatest extent among renewables. Fig. 2 illustrates the sources of electricity generation for at least one scenario from each of the studies.

The diverse range of renewable technologies reported across the studies reflects the location specificity of renewable resources. This diversity demonstrates the need for region-specific analyses to evaluate the market potential of renewable technologies. Although all studies come to the same general conclusion that RE can provide most (if not all) national, regional, or global electricity needs, the likely technology pathway (and the associated markets, policies, and infrastructure) will depend on the regional context.

Many of the scenarios (e.g., [15]) also make reference to the need for an intelligent operating system to facilitate access to greater flexibility, particularly from demand response. Studies cite many sources for flexibility, including storage (e.g., [12], with thermal storage and heat pumps; [18], through electric vehicles; [22], primarily through compressed air energy storage; [14,19,20], through hydro), demand management (all studies), gas turbines (e.g., [11,18,22]), balancing area coordination [14,22], and integration of cross-sectoral energy systems [11,12,15,16,18,21].

Several of the studies also estimate electricity costs for the scenario year. Some studies (e.g., [13,21,22]) suggest incremental cost increases under high RES-E systems; one study [12] shows “competitive” costs with the reference scenario; and Greenpeace [16] concludes that RES-E systems would be cheaper. Table 4 summarizes

**Table 2**
Demand data inputs in scenario analyses.

| Geographic Scope | Study | Demand data used in scenario analyses |
|---|---|---|
| Australia | Elliston et al. [11] | 2010 data used |
| Denmark | Lund and Mathiesen [12] | 2050: Electricity demand declines by 55% in private households and 33% in industry |
| Europe Union | ECF [13] | 2050: 4900 TWh/year (including Norway and Switzerland), compared with 3450 today; Aggressive EE would keep demand stable; the increase represents demand from electric vehicles and heat pumps for buildings and industry |
| Germany | SRU [14] | 2050: 500–700 TWh/year; the low-demand scenario, 500 TWh, represents lower energy demand than 2008 and would still allow half of the auto fleet to be electrified |
| Global | Greenpeace [16] | 2050: 46,500 TWh/year (12,800 TWh less than reference scenario, and over double today's global electricity generation) |
| Global | IEA [15] | 2050: 41,565 TWh/year, roughly double today's generation |
| Global | WWF [17] | 2050: Much reduced demand overall compared to BAU. Demand for power rises to over 35,000 TWh/year |
| Ireland | Connolly et al. [18] | 2007 data used |
| New Zealand | Mason et al. [19] | 2005–2007 data used |
| Portugal | Krajacic et al. [20] | 2006 data used |
| United Kingdom | Kemp and Wexler [21] | 2030: Double compared to current demand due to partial electrification of heat and transport sectors |
| United States | NREL [22] | 2050: 3920 TWh (low-demand scenario; annual growth rate of 0.17% from 2011 to 2050) |

**Table 3**
Example cost inputs in scenario analyses.

| Geographic scope | Study | Onshore wind | Capital technology costs in scenario year[a] | | | Discount rate | $CO_2$ cost |
|---|---|---|---|---|---|---|---|
| | | | Offshore wind | PV | NG-CC | | |
| Australia | Elliston et al. [11] | Prescribed dispatch order; did not assess cost implications | | | | | |
| Denmark | Lund and Mathiesen [12] | Based on official Danish technology data | | | | 3% real interest rate | $25/t |
| Europe Union | ECF [13] | −5% per doubling of cumulative installed capacity | | −15% per doubling | −0.5%/year | 7% real after-tax cost of capital | $110/t |
| Germany | SRU [14] | $0.06/kWh[b] | $0.05/kWh | $0.12/kWh | | 6% public sector interest rate | |
| Global | Greenpeace [16] | $1350/kW[c] | $2350/kW | $1060/kW | | | $75/t |
| Global | IEA [15] | $1500/kW[d] | $2150/kW | $1050–1300/kW | $1000/kW | 8%, presumably nominal | $150/t |
| Global | WWF [17] | $780/kW[e] | $1570/kW | $520/kW | | | |
| Ireland | Connolly et al. [18] | Study did not discuss cost implications | | | | | |
| New Zealand | Mason et al. [19] | Prescribed dispatch order; did not assess cost implications | | | | | |
| Portugal | Krajacic et al. [20] | Prescribed dispatch order; did not assess cost implications | | | | | |
| United Kingdom | Kemp and Wexler [21] | $1050–1450/kW[f] | $1830–2900/kW | $4330–7260/kW | $500–780/kW | | |
| United States | NREL [22][g] | $1980/kW | $2990/kW | $2030–2062/kW | $1230/kW | 8.9% nominal (5.7% real) | |

[a] The cost assumptions for most of the studies listed [12–16,22] are 2050 projections in USD; the exception is Kemp and Wexler [21], which uses 2030 cost projections.
[b] Only levelized cost information provided (nominal dollars, converted from Euros); study states that capital cost estimates are based on current costs projected onto future learning curves.
[c] Including costs for grid integration of up to 25% of investment; presumably nominal dollars.
[d] Overnight investment costs (2010 dollars).
[e] Nominal (2005) dollars, converted from Euros.
[f] Nominal (2005), converted from British Pounds.
[g] NREL [22] uses three separate cost and performance projections for renewable technologies and two separate projections for fossil technologies. Cost estimates are nominal dollars.

the estimated electricity costs from the studies that include estimates. One of the key results from NREL [22, p. iii] states, “improvement in the cost and performance of renewable technologies is the most impactful lever for reducing [the] incremental cost” of high renewable generation scenarios. IEA [15, p.371] states, “the overall $CO_2$ reduction target of the global energy system becomes the main force driving long term deployment of low-carbon power technologies in the 2DS” . None of the studies comprehensively evaluates the cost and benefits of their scenarios, including fuel security and risk and all environmental benefits.

### 4.5. Sensitivity analysis

Many of the studies rely on large and complex models that require an enormous supply of data. As such, most studies cannot systematically evaluate sensitivities with all inputs and we do not attempt to comprehensively review all model drivers. Nevertheless, several studies do run select sensitivity analyses. Examples include:

- Given the challenge of acquiring public support for new transmission, ECF [13] and NREL [22] both run sensitivity analyses to assess alternatives to transmission expansion, concluding that reduced anticipated transmission capacity is possible, but at higher costs and requiring combinations of increased storage, curtailments, and reserve capacity. Nevertheless, NREL [22] sensitivity analyses showed very modest cost increases ( $<$ \$0.005/kWh) relative to scenarios with greater transmission expansion.
- In addition to transmission sensitivity, NREL [22] also runs a number of sensitivities associated with technology costs, electricity demand, fossil fuel prices, resource accessibility, and constraints on the ability to manage variability. Even with constrained transmission, flexibility, or resources, the system could still work, and do so with very little increase in cost, because the renewable resource

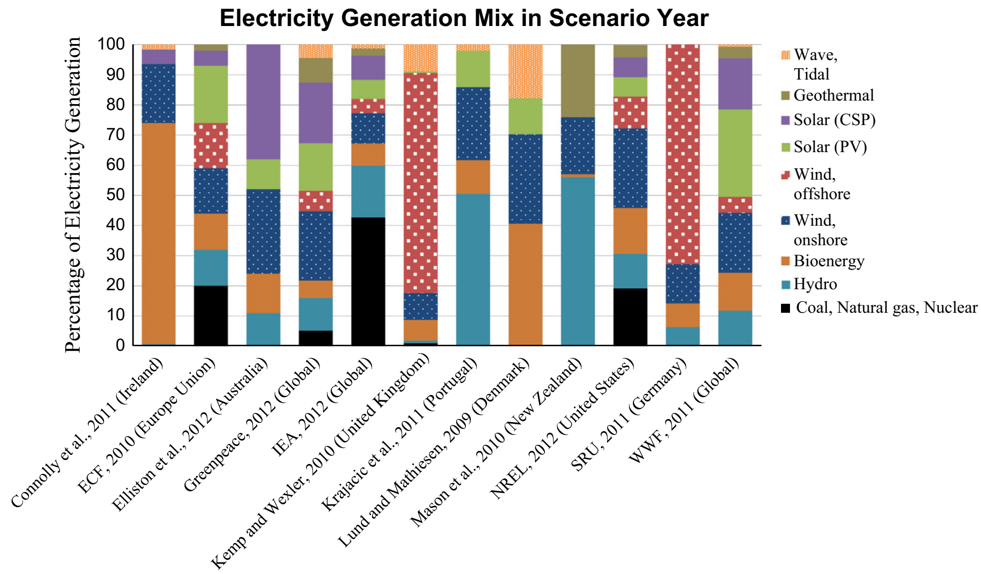


**Fig. 2.** Electricity generation mix in scenario year. Connolly et al. [18]: Numbers estimated from graph (combo scenario) by subtracting bio used in transportation, industry, and heating and then estimating percentages for rest of generation. ECF [13]: 80% RES; 10% CCS; 10% nuclear scenario. Elliston et al. [11]: estimated for this figure based on the combination of listed capacities, capacity factors, annual energy production, annual demand, and/or annual spilled energy. IEA [15]: 2DS (base). Krajacic et al. [20]: Closed system scenario. Lund and Mathiesen [12]: 2050 capacity projections for the scenario illustrated in the figure are 10,000 MW wind, 1000 MW wave, and 1500 MW PV; generation is not differentiated, but Lund [37], cited in the study, suggests proportional generation from RES-E to be 50% wind, 20% PV, and 30% wave. Mason et al. [19]: based on the modeling outputs in step 5, reflecting theoretical upper limits to hydro system operation. NREL [22]: 80% RE-ITI scenario. SRU [14]: scenario 2.2.a: Max 15% net import from Denmark and Norway; 500 TWh/year demand.

**Table 4**
Projected electricity costs in 2050.

| Geographic Scope | Study | Projected electricity costs in 2050 |
|---|---|---|
| Australia | Elliston et al. [11] | Scenario was simulation of 2010 power system using 100% RES-E, and therefore used actual 2010 data and did not create cost projections |
| Denmark | Lund and Mathiesen [12] | Costs would be competitive to reference scenario |
| Europe Union | ECF [13] | Unit electricity costs would be 10–15% higher than in baseline (excluding carbon pricing); however, energy costs per unit of economic output would decline 20–30% compared to the baseline |
| Germany | SRU [14] | \$0.12–0.16/kWh (inflation adjusted), depending on demand. Creating a large scale Europe–North Africa network would reduce prices to \$0.08–\$0.09/kWh. Expanding the German grid would entail additional costs of about \$0.013–\$0.026/kWh. |
| Global | Greenpeace [16] | \$7.9 cents/kWh below reference case. Long term costs for electricity supply are projected to be 22% lower in 2050 than in the reference scenario (including estimated costs for efficiency measures) |
| Global | IEA [15] | Reduction by \$26.0 USD trillion (2010) compared to 6DS (2010 dollars) for global electricity production |
| Global | WWF [17] | Costs for electricity grid extension, reinforcement, and balancing: \$155 billion per year (2005 dollars) |
| Ireland | Connolly et al. [18] | No costs provided. Analysis was from a technical and resource perspective, and not an economic perspective. Notes that future work will need to consider least-cost 100% RE system for Ireland |
| New Zealand | Mason et al. [19] | Used historic three-year data set as basis for costs. Simulation of current power system using 100% RES-E, and therefore did not create cost projections |
| Portugal | Krajacic et al. [20] | Scenarios did not include cost-based optimization |
| United Kingdom | Kemp and Wexler [21] | No electricity cost data provided |
| United States | NREL [22] | \$0.135–0.161/kWh average retail electricity price, which is \$0.024–0.05/kWh higher than 2050 baseline projections (nominal dollars) |

base is robust and diverse and thus can handle a wide range of conditions. The REF 80% scenarios are not highly sensitive to assumed conditions and scenarios.

- ECF's [13] additional sensitivity analyses conclude that discount rates, RES costs, and fuel prices "moderately" affect the price of $CO_2$ needed to bridge RES with carbon-based costs (i.e., those factors could impact projected electricity costs up to 15%).
- SRU [14] analyzes for sensitivity a number of factors (e.g., technology costs, electricity demand, and extent of energy exchange with neighboring countries), and finds, for example, that PV deployment is highly dependent on level of demand and availability to import/export. PV capacity reduces to zero in the low-demand/import scenarios.
- Elliston et al. [11] analyzes sensitivity to assess strategies to reduce reliance on biofuels and meet all hours of demand. Strategies include demand reduction, increased CSP plant capacities, increased CSP solar multiple, changed dispatch hours for CSP, and increased PV capacity on the presumption that price of PV modules will continue to fall. Simulations show all strategies are effective; increasing the CSP solar multiple is more effective than increasing CSP capacity; and reductions in peak-load demand in winter is possibly the most cost-effective, but economic analysis is needed to rank the options.
- Lund and Mathiesen [12] analyzes sensitivity of interest rates (doubling the 3% projected real interest rate to 6%) and of investments costs (up to 50% higher), and concludes that

RES-E remains competitive to the reference scenario. Also, the study's high biomass projections (used for CHP, industry, and transport) would require a significant reorganization of farming areas, which may not be realizable. Thus the study analyzes alternatives, including increasing wind capacity from 6000 MW to 15,000 MW to displace 200 PJ of biomass with hydrogen.

Projections to 2050 embody a high degree of uncertainty; therefore, sensitivity analyses with respect to the economic and political variables can inform possible ranges to results.

## 5. Implications for decision makers

Despite the differences, these studies share some common conclusions, one of which is that RE resources can play a large role in future power systems. Moreover, most of the studies address aspects of integrating these resources into system operations, and all of them conclude that RES-E can supply, on an hourly basis, a majority of a country's or region's electricity demand. Other insights common to the studies include:

*Technology trends*: All studies—reflecting a large range in system sizes, locations, and other factors—conclude that high RES-E is possible. Furthermore, to achieve this, many of these scenarios (e.g., [11–14,22]) state that technology breakthroughs are unnecessary; nevertheless, significant operational and policy changes are required. Many studies also articulate the benefits of systems integration. For example, Elliston et al. [11] and IEA [15] conclude that transitioning from supply- and demand-driven perspectives toward systems integration is one of the most important challenges in transitioning to a high RES-E scenario. Finally, some of the studies offer assessments for country-specific technology decisions; e.g., SRU [14] concludes that energy security could be maintained if coal and nuclear plants are retired at the end of their service lives, with no extensions.

*New transmission and public support*: Many studies (e.g., [13–15,17,21,22]) conclude that significant grid investments will be required in the near future to achieve high RES-E penetrations. Some of these studies [13–15] extend this policy implication to recommend that a critical action by government would be to promote social acceptance of new grid infrastructure. The ECF [13] study concludes that the toughest challenge is to obtain public support for the transformation to high RE-futures, requiring breakthroughs in practice compared to today. SRU [14] highlights the need for government to use leadership to overcome the path dependence of the current system.

*Coordinated planning and regional cooperation*: The need for coordination is a common theme among the studies that evaluate benefits from regional cooperation, including ECF [13], SRU [14], WWF [17], and NREL [22]. For example, SRU [14] concludes that coordination with the EU is essential because 100% RES-E supply requires strong coordination with EU energy and climate policies. Also, larger, more integrated markets and grids improve reliability of high RES-E futures (see, e.g., [13,14,22]). SRU [14] and WWF [17] suggest a strong role for government coordination in order to facilitate investment certainty. IEA [15] references the need for coordinated government policy action to reduce the main barrier to a low-carbon future, which is, according to the study, the unequal distribution, in time and across counties, of the costs and benefits associated with high RES-E.

*Increased flexibility*: Gas generation (e.g., natural gas combined cycle) is cited as a key component of system flexibility in several studies (e.g., [12,15,18,22]), given the ability of gas generators to quickly ramp up and down, among other flexible attributes. Initially, some of the studies project a strong role for natural gas, but as RES-E penetrations rise, the source of fuel in many studies shifts to emerging technologies, such as biogas. Other technologies also offer flexibility. For example, SRU [14], Mason et al. [19], and Krajacic et al. [20] scenarios employ hydro as a key source of flexibility. Lund and Mathiesen [12] relies on CHP for its thermal storage (to absorb wind capacity) and to generate dispatchable electricity. Several studies (e.g., [13–15,19,21,22]) suggest changes to markets and operations to improve net system flexibility (e.g., diversifying the location of wind generation sites and enlarging balancing areas). ECF [13] models a role for responsive, "smart" demand to improve system flexibility. IEA [15] modeling results conclude that a smarter grid would offer four-to-one returns on investment, and that demand response, depending on the region, could supply all the necessary regulation and load-following to improve system flexibility. Kemp and Wexler [21] concludes that electric cars could help minimize the need for new grid capacity and decrease total system costs.

*Cost reductions*: Several studies [13,21,22] indicate that there are incremental costs associated with a transition to a RES-E based power system, but that R&D could reduce these costs. Greenpeace [16] and WWF [17] also stress the importance of public investment in research and development to reduce costs. Some of the studies [15,16,21] recommend policies that level the playing field for clean energy by reducing fossil fuel subsidies and/or implementing carbon prices, though the studies conclude that these measures alone would be insufficient to achieve high RES-E penetrations, and therefore suggest additional measures such as targets or feed-in tariffs.

*Sensitivity to weather*: The studies all assume a particular weather year(s) in the scenario analyses. Further examination of the range of weather years that will occur over the time period of build-out to a high RE system would improve our understanding of how robust the choice of RE technologies is to wide ranges in weather over time, particularly with expected climate change over this period.

## 6. Conclusion

Comparing various studies that consider the high penetration of RE generation at the national, regional, and global levels has allowed us to distill a set of generalized implications for decision makers. The technology mix at high RES-E penetrations varies considerably regionally and globally, and therefore suggests that continued R&D across the broad spectrum of RE technologies may benefit RE industries at multiple locations. More research is needed to understand the unique market opportunities for different RE technologies and the interactions among increasingly global markets.

The set of conditions necessary to create enabling environments for this diversity in RES-E growth varies dramatically across jurisdictions, and varying scenarios and sensitivities can help inform their design. Assumptions about areas ranging from cost to the suite of technologies in the generation portfolio will have considerable impacts on results – especially in the long term. Meta-analysis can help highlight those factors that are most important in this regard.

To this end, the comparison analysis of RES-E studies suggests fruitful areas for research. Cost implications for high RES-E futures were not consistent or even uniformly assessed among the selected studies. Because economically based capacity expansion and dispatch models have not been the focus of most RES-E studies, this type of modeling would thus be a suggested area for continued research.

Also, although all of the studies project cost-effective roles for energy efficiency to decrease power sector costs and meet demand, the studies do not fully model the role for demand response to address some of the technical challenges of high RES-E. This insufficient treatment of demand-side opportunities reflects the broader need for continued research to understand the full value and adoption potential of demand response, particularly in how they can be used to facilitate renewable grid integration.

While the breadth, depth, geographic diversity, and range of technical sophistication across the many energy scenarios vary considerably, an increasing body of analysis suggests that high RE scenarios may be feasible in many locations. Further research that evaluates these potential pathways in greater detail, including full system reliability analysis, greater sensitivity to uncertainty, and analyses of markets and utility business models will be critical to advancing our understanding.

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